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## Search for heavy vector-like quarks coupling to light quarks in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector<sup>☆</sup>

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### ARTICLE INFO

#### Article history:

Received 24 December 2011

Received in revised form 9 March 2012

Accepted 29 March 2012

Available online 2 April 2012

Editor: H. Weerts

### ABSTRACT

This Letter presents a search for singly produced vector-like quarks,  $Q$ , coupling to light quarks,  $q$ . The search is sensitive to both charged current (CC) and neutral current (NC) processes,  $pp \rightarrow Qq \rightarrow Wqq'$  and  $pp \rightarrow Qq \rightarrow Zqq'$  with a leptonic decay of the vector gauge boson. In  $1.04 \text{ fb}^{-1}$  of data taken in 2011 by the ATLAS experiment at a center-of-mass energy  $\sqrt{s} = 7$  TeV, no evidence of such heavy vector-like quarks is observed above the expected Standard Model background. Limits on the heavy vector-like quark production cross section times branching ratio as a function of mass  $m_Q$  are obtained. For a coupling  $\kappa_{qQ} = v/m_Q$ , where  $v$  is the Higgs vacuum expectation value, 95% C.L. lower limits on the mass of a vector-like quark are set at 900 GeV and 760 GeV from CC and NC processes, respectively.

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### 1. Introduction

Vector-like quarks (VLQ), defined as quarks for which both chiralities have the same transformation properties under the electroweak group  $SU(2) \times U(1)$ , are predicted by many extensions of the SM, relating to Grand Unification, dynamical electroweak symmetry breaking scenarios or theories with extra dimensions [1–10]. Since the couplings of the light quarks are well constrained, if VLQs exist they are generally expected to only couple sizably to the third generation. However, in certain scenarios, corrections to quark mixings can cancel, relaxing these constraints. The motivation and phenomenology of heavy VLQs coupling to light generations is discussed for the Tevatron [11], where a baseline model is introduced which considers two degenerate VLQ doublets having hypercharges  $1/6$  and  $7/6$  and mixing only with the up quark. This scenario can occur naturally in certain models [12]. Because the doublets are degenerate, cancellations occur which allow VLQ coupling to the first two generations, leading to a potentially strong signal at the Large Hadron Collider (LHC).

Following the notation of more recent work [13] which describes a model-independent approach to VLQ sensitivity at the LHC, a coupling  $\kappa_{qQ} = (v/m_Q)\tilde{\kappa}_{qQ}$  is defined here, where  $q$  stands for any light quark,  $Q$  is the VLQ,  $m_Q$  is the VLQ mass,  $v$  is the Higgs vacuum expectation value and  $\tilde{\kappa}_{qQ}$  encodes all the model dependence of the  $qVQ$  vertex ( $V = W$  or  $Z$ ). Electroweak precision measurements constrain the contribution of heavy quarks to loop diagrams, but under certain conditions, as for the degenerate

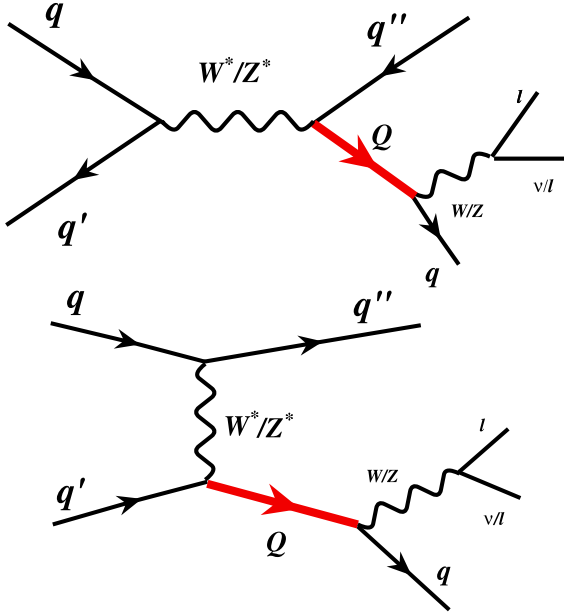
VLQ doublet model above, mild bounds apply on the dimensionless coupling  $\kappa$ , allowing it to be as large as  $\sim 1$  [13]. The masses of VLQs are not constrained by vacuum stability in the SM [14].

It has been shown that single production provides a favorable process to probe for the existence of these heavy quarks if the coupling to light quarks is large, and that a significant mass reach could be achieved at the LHC with early data [11,13]. Single production of a VLQ occurs via the process  $qq' \xrightarrow{V^*} q''Q$  (Fig. 1). A quark produced by this process of gauge boson exchange can have a charge of  $5/3$ ,  $2/3$ ,  $-1/3$  or  $-4/3$ . As a benchmark, we consider theories with only VLQs  $U$  of charge  $+2/3$  or only with  $D$  of charge  $-1/3$ , without regard to the multiplet structure of the model. The experimental limits obtained on cross section times branching ratio can then be interpreted as limits on the couplings for different VLQ models [13]. The contribution from the  $s$ -channel diagram is negligible compared to that of the  $t$ -channel process. Therefore one characteristic of the signal is the presence of a forward jet: after one of the initial state quarks emits the electroweak gauge boson, it will continue in the forward direction with little transverse momentum ( $p_T$ ), while the other quark couples to the  $W$  or  $Z$  to produce the heavy quark. Because the LHC is a proton–proton collider, the charged current (CC) production of a  $D$  quark is expected to have a higher cross section than that of a  $U$  quark. Similarly, for the neutral current (NC) process,  $U$  quarks are expected to be produced more abundantly. Anti-quark production is suppressed since it involves anti-quarks in the initial state.

Bounds on the mass of new heavy quarks were obtained previously from a search in the pair production process at the Tevatron [15,16] and LHC [17,18]. Limits have also been obtained at the Tevatron [19,20] on single production processes  $\sigma(p\bar{p} \rightarrow qQ) \times \text{BR}(Q \rightarrow qW)$ , which in the model [11] of degenerate doublets

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**Fig. 1.** Vector-like quark production and decay diagrams for s-channel (top) and t-channel (bottom). The thick line indicates the vector-like quark.

with  $\tilde{\kappa}_{uD} = 1$  and decaying 100% via CC gives a 95% confidence level (C.L.) upper limit exclusion for  $D$  quarks with masses up to 690 GeV. Limits at 95% C.L. on  $\sigma(p\bar{p} \rightarrow qQ) \times \text{BR}(Q \rightarrow qZ)$  in the same model yield an exclusion of a  $U$  quark with  $\tilde{\kappa}_{uU} = \sqrt{2}$  and 100% branching ratio via NC up to a mass of 550 GeV.

This Letter reports on a search for singly produced VLQs in the ATLAS detector at the LHC. The search is conducted in events with at least two jets and a vector boson, indicated by either two high- $p_T$  leptons (electrons or muons) in the case of a  $Z$ , or a single lepton and missing transverse momentum ( $E_T^{\text{miss}}$ ) in the case of a  $W$ . The data used in this analysis were collected from March to June 2011, at a center-of-mass energy  $\sqrt{s} = 7$  TeV and correspond to an integrated luminosity of  $\mathcal{L} = (1.04 \pm 0.04) \text{ fb}^{-1}$  [21].

## 2. The ATLAS detector

The ATLAS detector is a multi-purpose particle physics detector system optimized to record information coming from  $pp$  collisions [22]. Closest to the interaction point is the inner detector (ID) for charged particle tracking, which is performed by silicon pixel and microstrip detectors in addition to a straw-tube tracker with radiators to produce transition radiation. The tracking system is embedded in a 2 T axial magnetic field. Surrounding the solenoid are the lead and liquid argon electromagnetic (EM) calorimeter and hadronic tile calorimeter subsystems. Forward calorimetry is accomplished with liquid argon detectors and copper and tungsten absorbers. These systems allow the reconstruction of electrons and jets, both essential for this analysis. Surrounding the calorimeter systems is a muon spectrometer (MS) that uses drift chambers to record muon trajectories in a toroidal magnetic field. A three-level trigger is used to select events for subsequent offline analysis. Events recorded when a subsystem was not properly functioning are not used in this analysis.

## 3. Signal and background modeling

Signal Monte Carlo (MC) samples are generated using MadGraph [23] based on Refs. [11,13], then hadronized and showered through PYTHIA [24]. The CTEQ6L1 parton distribution function

(PDF) [25] is used, with factorization and renormalization scales of  $m_W$  ( $m_Z$ ) for the CC (NC) channel. Nine reference masses are generated for both CC and NC decays: 225 GeV, 300 GeV, then continuing in steps of 100 GeV up to 1 TeV. The production cross section times branching ratio to a vector boson and jets ranges from 194 pb to 0.47 pb for CC and from 88 pb to 0.28 pb for NC, assuming  $\tilde{\kappa}_{qQ} = 1$ .

The dominant SM backgrounds are  $W \rightarrow \ell\nu + \text{jets}$  and  $Z \rightarrow \ell\ell + \text{jets}$  for the CC and NC channels, respectively. Other sources of background are from multijet events,  $t\bar{t}$ , single top, and diboson processes, which can have electrons or muons and jets in the final states. With the exception of multijets, the contributions of these backgrounds are estimated using MC samples.  $W + \text{jets}$  and  $Z + \text{jets}$  samples are generated by ALPGEN [26] using CTEQ6L1 PDFs with parton showering performed by HERWIG [27] and using JIMMY [28] for simulation of the underlying event model. The cross section times leptonic branching ratios are 10.3 pb and 1.06 pb per lepton flavor for  $W$  and  $Z$ 's, respectively, with  $p_T$  of the leptons  $> 20$  GeV. This includes  $K$ -factors of 1.22 and 1.25, respectively, to reproduce the inclusive cross sections at next-to-leading order in QCD [29]. MC@NLO [30] is used to simulate  $t\bar{t}$  production, giving a cross section of 165 pb. Single top quark events decaying leptonically ( $\sigma = 37.5$  pb) are generated with AcerMC [31] combined with parton showering and hadronization by PYTHIA. Diboson backgrounds are simulated with ALPGEN and HERWIG parton shower for the NC channel ( $\sigma \times \text{BR} = 5.97$  pb), which requires two leptons in the final state, and standalone HERWIG (with a  $K$ -factor of 1.52 to reproduce the inclusive cross section at next-to-leading order in QCD [32]) for the CC channel ( $\sigma \times \text{BR} = 69.1$  pb) where a single lepton is required. Multijet backgrounds from QCD processes are derived both from PYTHIA and data samples, described below.

The detector response simulation [33] is based on GEANT4 [34, 35]. The MC samples are generated with superimposed minimum bias events to simulate the conditions that occur in data. In order to improve the modeling of both signal and backgrounds, lepton reconstruction and identification efficiencies, energy scales and resolutions in the MC are corrected to correspond to the values measured in the data.

## 4. Analysis

The analysis is subdivided into four channels: charged and neutral current, each with either electrons or muons in the final state. Particle definitions and selections are identical in all channels, but signal and control regions for the CC and NC channels are defined independently.

Events are selected in which there is at least one vertex reconstructed with at least three tracks. The vertex with the greatest total transverse momentum,  $\sum |p_T|$ , of the associated tracks is designated as the primary vertex. The trigger requires at least one cluster in the EM calorimeter with  $p_T > 20$  GeV or at least one muon candidate in the MS with a track originating from the primary vertex with  $p_T > 18$  GeV. In both cases, the trigger requires a matching ID track.

Electron candidates are required to pass tight quality selection criteria based on the calorimeter shower shape, track quality and track matching with the calorimeter cluster [36]. They must have  $p_T > 25$  GeV and lie in the pseudorapidity<sup>1</sup> region  $|\eta| < 2.47$ , excluding the regions of transition between the central and forward detector sub-elements,  $1.37 < |\eta| < 1.52$ . During most run periods

<sup>1</sup> ATLAS uses a right-handed coordinate system with the  $z$ -axis along the beam pipe. The  $x$ -axis points to the center of the LHC ring, and the  $y$ -axis points upward. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

of the data set, a region of the EM calorimeter corresponding to about 1% of channels was less efficient than the rest of the detector. An exclusion window around the affected area was defined as  $-0.1 < \eta < +1.5$  in pseudorapidity and  $-0.9 < \phi < -0.5$  in azimuth. Electrons in this region are removed from data collected during these periods. The same procedure is applied to simulated events corresponding to the fraction of data covered by these run periods. Finally, no more than 4 GeV of transverse energy is allowed outside the core of the electron defined by a cone of size  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ .

Muon candidates are reconstructed by combining tracks from both the ID and the MS. They are required to pass ID quality requirements [37] and have  $p_T > 25$  GeV and  $|\eta| < 2.4$ . To suppress cosmic rays, muon candidates must have a distance of closest approach to the primary vertex in the longitudinal direction  $|z_0| < 5$  mm and in the transverse plane  $|d_0| < 0.1$  mm. Isolated muons are selected by requiring that the sum of ID track transverse momentum around the muon track, in a cone of  $\Delta R = 0.2$  divided by the  $p_T$  of the muon itself be less than 0.1.

Jet four-vectors are reconstructed from calorimeter clusters using the anti- $k_T$  algorithm [38] with a radius parameter of 0.4. After correcting for calorimeter non-compensation and inhomogeneities by using  $p_T$ - and  $\eta$ -dependent calibration factors [39], jets are required to have  $p_T > 25$  GeV and  $|\eta| < 4.5$ . Events containing jets that fail quality criteria [40] are rejected to ensure an accurate  $E_T^{\text{miss}}$  measurement. Furthermore, events containing jets passing through the inefficient region of the EM calorimeter are vetoed. To remove jets originating from other  $pp$  interactions within an event, the selected jets are required to have more than 75% of  $p_T$ -weighted ID tracks associated to the primary vertex. Finally, to avoid counting electrons as jets, any jet candidate within  $\Delta R < 0.2$  of a selected electron is removed.

The  $E_T^{\text{miss}}$  is calculated as the negative vector of the transverse components of energy deposits in the calorimeters within  $|\eta| < 4.5$ . For events containing muons, any calorimeter energy deposit from a muon is ignored and the muon energy measured in the MS is used instead [41].

The CC candidates are required to have (i) exactly one electron or muon, (ii) missing transverse momentum  $E_T^{\text{miss}} > 50$  GeV, (iii) one jet with  $p_T > 50$  GeV and at least one more jet with  $p_T > 25$  GeV, (iv) a minimum pseudorapidity separation  $|\Delta\eta| > 1.0$  between the highest- $p_T$  (leading) jet and second or third-leading jet, since the presence of a forward jet is expected in signal events, (v)  $m_T(\ell, E_T^{\text{miss}}) > 40$  GeV, where  $m_T(\ell, E_T^{\text{miss}}) = \sqrt{2E_T^{\text{miss}} E_T^\ell (1 - \cos\Delta\phi_{\ell, E_T^{\text{miss}}})}$  is the transverse mass of the  $W$  candidate, and (vi) an azimuthal angle separation between the lepton and  $E_T^{\text{miss}}$  vector  $\Delta\phi_{\ell, E_T^{\text{miss}}} < 2.4$  rad since the  $W$  in the signal is expected to be boosted. To reconstruct the mass of the VLQ candidate, the longitudinal momentum  $p_z$  of the neutrino is calculated such that the invariant mass of the lepton and  $E_T^{\text{miss}}$  equals the mass of the  $W$ . Of the two solutions, the one which leads to the larger value of  $|\Delta\eta|$  between the reconstructed neutrino four-vector and the leading jet is chosen, since the simulation shows it to be the correct solution about 60% of the time. If no real solution is found, the real part of the complex solutions is taken. The system composed of the leading jet and the reconstructed  $W$  is taken to be the VLQ candidate.

The NC candidates are required to have exactly two oppositely charged same-flavor leptons with an invariant mass in the range  $66 < M(\ell, \ell) < 116$  GeV and a transverse momentum  $p_T(\ell, \ell) > 50$  GeV. At least two jets of  $p_T > 25$  GeV are required, with the same  $|\Delta\eta| > 1.0$  requirement as described for the CC selection. The invariant mass of the system composed of the two leptons and the leading jet is taken to be the VLQ candidate mass.

**Table 1**

Expected and observed event counts in the kinematically allowed VLQ mass range after the final selection in the CC channel with an integrated luminosity of  $1.04 \text{ fb}^{-1}$ . Uncertainties are statistical and systematic, respectively. The signal predictions assume a coupling  $k_{UD} = 1$ .

Process	Electron channel	Muon channel
$W + \text{jets}$	$14\,500 \pm 100 \pm 4400$	$16\,600 \pm 100 \pm 5000$
$t\bar{t}$	$2360 \pm 50 \pm 270$	$2530 \pm 50 \pm 290$
Single top	$700 \pm 30 \pm 120$	$740 \pm 27 \pm 120$
Multijet	$670 \pm 30 \pm 270$	$340 \pm 20 \pm 410$
$Z + \text{jets}$	$128 \pm 11 \pm 90$	$432 \pm 21 \pm 170$
Diboson	$174 \pm 13 \pm 53$	$198 \pm 14 \pm 62$
Expected total background	$18\,500 \pm 100 \pm 4400$	$20\,900 \pm 100 \pm 5100$
Data	17 302	20 668
Expected signal, $D(225 \text{ GeV})$	$2360 \pm 50 \pm 350$	$2380 \pm 50 \pm 400$
Expected signal, $D(600 \text{ GeV})$	$133 \pm 12 \pm 10$	$133 \pm 12 \pm 11$
Expected signal, $D(1000 \text{ GeV})$	$14 \pm 4 \pm 1$	$14 \pm 4 \pm 1$

To evaluate the level of multijet background in the CC analysis, a procedure is used based on a fit to the  $E_T^{\text{miss}}$  distribution in the range  $0 < E_T^{\text{miss}} < 100$  GeV. For this purpose, only selection criteria (i) and (v) above are required. For both the electron and muon modes, template shapes for the non-multijet backgrounds are taken from the MC samples described earlier and summed according to their relative cross sections. The overall normalization of this non-multijet template is left floating. In the electron mode, a sample enriched in objects misidentified as electrons (fakes) is selected from data using *medium* quality electrons, excluding *tight* electrons, as defined in [36]. The  $E_T^{\text{miss}}$  distribution of this sample serves as the electron multijet template shape. For the muon mode, multijet background is primarily expected to come from heavy-flavor decays. Therefore, the multijet template shape is taken from a PYTHIA sample of  $b\bar{b}$  events. For both lepton flavors, a fit to the  $E_T^{\text{miss}}$  distribution is performed using the multijet and non-multijet templates to determine the normalization of the multijet component. The modeling of the multijet background was tested in a control region defined by the range of  $10 < E_T^{\text{miss}} < 30$  GeV. The modeling of the kinematic variable distributions, and in particular of the VLQ candidate mass, was found to agree with data within statistics.

In the case of the NC selection, the multijet background is estimated from data-driven studies to be negligible. In the electron channel the selection for electron candidates is changed to require the medium criteria, excluding tight electrons, to obtain a fake dielectron template shape in  $m_{ee}$ , which is then scaled to make the total background expectation match the data with the same selection. In the muon channel the isolation requirement is inverted, and the  $m_{\mu\mu}$  template scaled to the data in the same way.

With the above selections, the observed event yields and corresponding predictions are given in Tables 1 and 2. From these yields, no significant excess is observed in the data that can be accounted for by a VLQ signal. Fig. 2 shows the invariant mass distributions of the reconstructed VLQ candidate in the signal regions for both channels. These distributions are used in a binned likelihood fit to extract signal yields and production cross section upper limits. A slight shape discrepancy between data and MC is apparent in Fig. 2. Before extracting an upper limit, a correction is applied to the MC background shape, as described in Section 6.

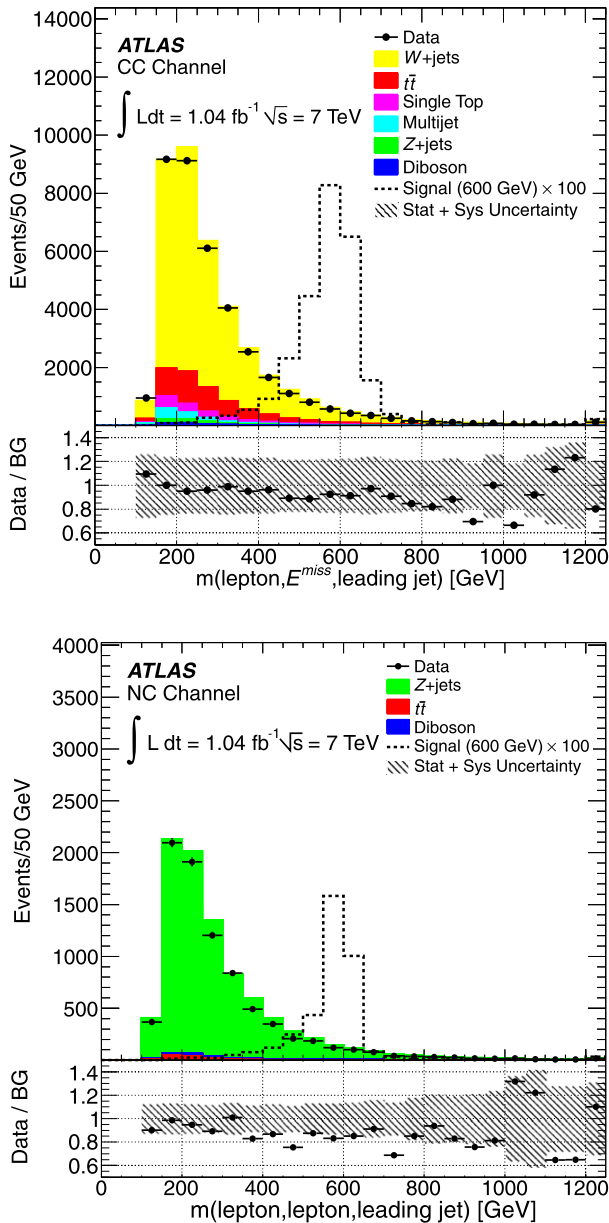
## 5. Systematic uncertainties

Systematic uncertainties on the simulation of the signal arise from uncertainties in PDFs and the factorization and renormalization scales. In order to estimate the uncertainty due to the parton

**Table 2**

Expected and observed event counts in the kinematically allowed VLQ mass range after the final selection in the NC channel with an integrated luminosity of  $1.04 \text{ fb}^{-1}$ . Uncertainties are statistical and systematic, respectively. The signal predictions assume a coupling  $\tilde{\kappa}_{UU} = 1$ .

Process	Electron channel	Muon channel
Z + jets	$3250 \pm 60 \pm 430$	$5350 \pm 70 \pm 700$
$t\bar{t}$	$58 \pm 8 \pm 3$	$90 \pm 9 \pm 5$
Diboson	$38 \pm 6 \pm 4$	$58 \pm 8 \pm 4$
Expected total background	$3350 \pm 60 \pm 430$	$5500 \pm 70 \pm 700$
Data	3105	5070
Expected signal, $U(225 \text{ GeV})$	$192 \pm 14 \pm 9$	$339 \pm 18 \pm 19$
Expected signal, $U(600 \text{ GeV})$	$15 \pm 3.9 \pm 0.6$	$23 \pm 4.8 \pm 0.7$
Expected signal, $U(1000 \text{ GeV})$	$1.9 \pm 1.4 \pm 0.1$	$2.7 \pm 1.6 \pm 0.1$



**Fig. 2.** Invariant mass distribution of VLQ candidates in both the CC (top) and NC (bottom) channels, summed over both the electron and muon final states. The dashed line shows the signal shape, normalized by 100 times the leading-order theoretical cross section. The bottom part of each plot shows the ratio of the data to the background model. The last bin contains events with invariant mass candidates equal to or higher than 1200 GeV.

distributions, the CTEQ66 [42] PDF set is used, for which the eigenvectors of the Hessian matrix are known. The difference in signal cross section due to the PDF uncertainty is found to range from 3.0% at a signal mass of 225 GeV to 4.4% at 1000 GeV. The uncertainty due to the factorization and renormalization scales is estimated by taking the difference between signal cross sections at the nominal value of the scales, and at values of one-half and twice the nominal. The uncertainty is found to vary between 4% and 12% for the same mass range. Uncertainties due to the simulation of initial and final state radiation are found to be about 1%. These uncertainties on the theoretical cross section are added in quadrature.

For signal and background events, the jet-energy-scale uncertainty is calculated by shifting the  $p_T$  of all jets up and down by factors that vary as a function of  $p_T$  and  $\eta$ . The factors range from 4.6% for jets with  $p_T = 20 \text{ GeV}$  to 2.5% for jets with  $p_T$  above 60 GeV [39]. This procedure results in an uncertainty of about 20% on the background normalization, and about 5% on the signal efficiency. The jet-energy-resolution uncertainty is calculated by smearing the  $p_T$  of each jet depending on the jet  $p_T$  and  $\eta$ , typically by around 10%. This source of uncertainty is found to impact both the background normalization and signal efficiency by about 1%. The lepton-energy-scale uncertainty is evaluated and found to be much less than 1% for both signal and background. The effect of the previously mentioned EM calorimeter inefficiency is also found to be much less than 1%. Uncertainties also arise from the trigger, identification, and reconstruction efficiency corrections applied to the MC simulation. They affect the signal efficiency uncertainty by 1–2% depending on the mass. The rate uncertainty from MC statistics after event selection is 3–5%. Finally, the uncertainty on the luminosity is 3.7% [21]. None of the systematics studied have been found to significantly affect the shape of the VLQ candidate mass distribution.

## 6. Results

To determine signal yields, a binned maximum likelihood fit is performed using template histograms of the VLQ candidate mass distribution. The fit is performed separately for each signal mass. The electron and muon final states are fitted simultaneously. The overall signal and background normalizations are left floating in the fit. Systematic uncertainties on the template normalizations are incorporated as Gaussian-distributed nuisance parameters, as are the signal efficiency systematics used in determining the cross section limits. Signal template shapes are taken from MC, while background templates are as shown in Fig. 2, with an additional correction described next.

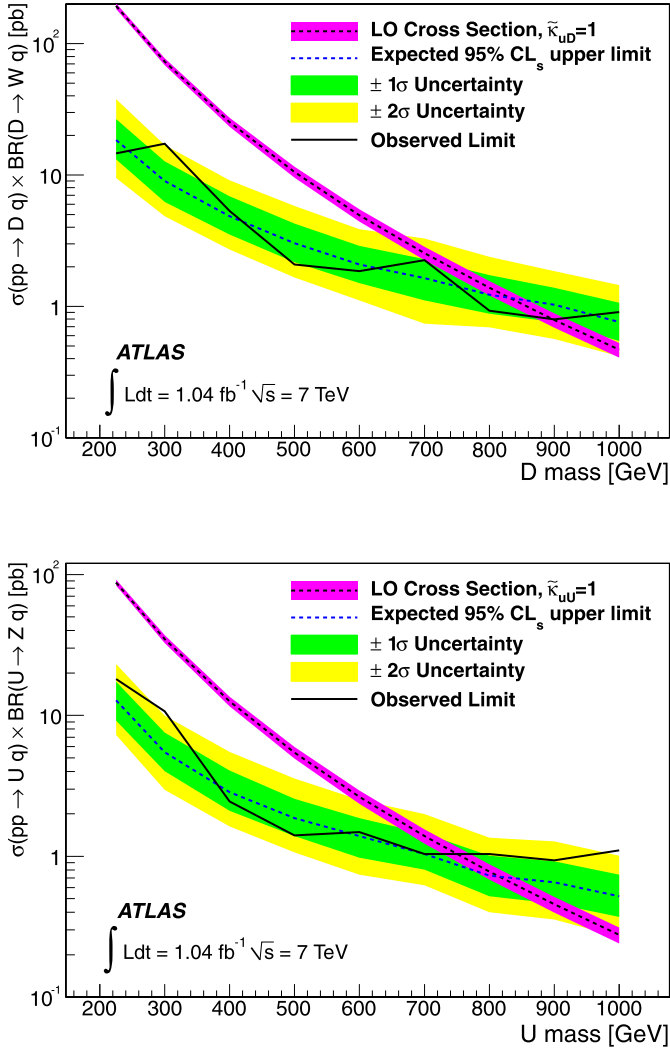
A heavy VLQ signal would appear as a peak on top of a smooth background in the VLQ candidate invariant mass distribution. It is therefore important to have a good estimate of the background shape in the region around a signal mass hypothesis. The fit procedure described above makes use of the full range of mass, but the normalization is dominated by the lower mass region where the number of events is higher. A small shape difference between Monte Carlo and data can therefore yield a systematic bias in the fit at high mass. For that reason a correction is applied to the background model for each signal mass. It is obtained from linear fits to the reconstructed invariant mass of the ratio of data/MC after the full event selection, excluding bins in the range  $[-200, +100] \text{ GeV}$  around each signal mass tested. The asymmetric choice in the excluded mass is motivated by the fact that the expected signal has a low mass tail. The  $1\sigma$  uncertainty in the slope is taken as a systematic shape uncertainty. It was verified that no significant difference to the fit results arose from choosing a narrower excluded mass window, or even no exclusion at all.



**Table 3**

Observed upper limits at 95% confidence level on the cross section times branching ratio  $\sigma(pp \rightarrow Qq) \times \text{BR}(Q \rightarrow Vq)$  as a function of mass and the corresponding upper limit on a model-independent heavy-to-light quark coupling. The final column shows the limit on the CC process after selecting negatively charged leptons.

Mass [GeV]	CC $\sigma \times \text{BR}$ [pb]	NC $\sigma \times \text{BR}$ [pb]	$\tilde{\kappa}_{uD}^2$	$\tilde{\kappa}_{uU}^2$	CC <sup>-</sup> $\sigma \times \text{BR}$ [pb]
225	15	18	0.075	0.21	12
300	17	11	0.24	0.31	5.6
400	5.3	2.4	0.21	0.19	3.8
500	2.1	1.4	0.19	0.26	1.1
600	1.9	1.5	0.37	0.56	1.9
700	2.2	1.0	0.86	0.75	2.2
800	0.93	1.0	0.66	1.33	0.97
900	0.80	0.9	1.0	2.1	0.70
1000	0.91	1.1	1.9	4.0	0.50



**Fig. 3.** Upper limits at 95% confidence level on the cross section times branching ratio  $\sigma(pp \rightarrow Qq) \times \text{BR}(Q \rightarrow Vq)$  for the CC (top) and NC (bottom) channels as a function of mass. The leading-order (LO) theoretical cross section assumes  $\tilde{\kappa}_{uD} = 1$  and  $\tilde{\kappa}_{uU} = 1$  on the top and bottom, respectively. The width of the dark band around it corresponds to the theoretical uncertainty described in the text. The expected cross section upper limit is determined by the median result of background-only pseudoexperiments, and is shown with its  $1\sigma$  and  $2\sigma$  uncertainties, respectively.

Since no significant excess of data over the background prediction is observed in either channel, limits as function of the VLQ mass are obtained based on the likelihood fits. Pseudoexperiments are generated by sampling the likelihood function to compute the expected limits, using a Gaussian prior for all nuisance param-

eters and including the shape uncertainty from the linear correction.

The 95% C.L. exclusion limits on  $\sigma(pp \rightarrow Qq) \times \text{BR}(Q \rightarrow Vq)$  as a function of the VLQ mass, based on the  $\text{CL}_s$  method [43], are shown in Fig. 3. Taking the intersection of the observed (expected) cross section limits with the central value of the theoretical cross section, masses below 900 GeV (840 GeV) are excluded for the CC channel and 760 GeV (820 GeV) for the NC channel, assuming a coupling  $\tilde{\kappa}_{qQ}^2 = 1$  and a 100% branching ratio for VLQs to decay to a vector boson and a jet. Within the  $\pm 1\sigma$  theoretical uncertainties, the observed CC mass limit ranges from 870–920 GeV. The corresponding range for the NC limit is 730–770 GeV. Limits for each mass tested are given in Table 3. The fourth and fifth columns show an interpretation of the cross section limits in terms of limits on the couplings  $\tilde{\kappa}_{uD}^2$  and  $\tilde{\kappa}_{uU}^2$ , in each case assuming only  $D$  production or only  $U$  production, respectively, and 100% branching fraction to a vector boson and jet.

A stronger limit in the CC channel may be obtained by repeating the CC analysis, requiring a negatively charged lepton because the SM background from  $W^- + \text{jets}$  is lower than for  $W^+ + \text{jets}$ . The upper limits on  $\sigma(pp \rightarrow D^{-\frac{1}{3}}q) \times \text{BR}(D^{-\frac{1}{3}} \rightarrow W^-u)$  are given in the sixth column of Table 3.

## 7. Conclusion

A search for single production of vector-like quarks coupling to light generations has been presented. No evidence is found for such quarks above the expected background in either the CC or NC channel. Upper limits on the production cross section times branching ratio to a vector boson and a jet were determined at 95% confidence level. Assuming couplings  $\tilde{\kappa}_{uD}^2 = 1$  and  $\tilde{\kappa}_{uU}^2 = 1$ , the upper bounds obtained for the mass of vector-like quarks are 900 GeV for the CC channel and 760 GeV for the NC channel. These limits, which can be used to constrain different models of vector-like quarks [13], are the most stringent to date on this benchmark model.

## Acknowledgements

We thank A. Atre, M. Carena, T. Han, and J. Santiago for the MadGraph code used to produce the signal MC samples.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF,

DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYs (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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